Feature

Life Cycle Assessment: A Tool for Determining the Environmental Impact of Horticultural Crop Production

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Summary. System-level research has resulted in significant advancements in horticultural crop production. Contributions of individual components to production efficiency, cost, and environmental impact have been a focus of such research. Public awareness of the environmental impact of products and services is increasing. Life cycle assessment (LCA) is a tool to study horticultural crop production systems and horticultural services and their individual components on environmental impacts such as the carbon footprint, stated as global warming potential. This manuscript introduces LCA and describes how this tool can be used to generate information important to the industry and consuming public.

The consuming public is becoming more concerned about the impact of their purchases and activities on the environment. Special interest groups and marketers are increasing public awareness through news stories and advertisement. Terms such as "sustainable," "green," and "reduced carbon footprint" are being used in conversations and promotions. Indeed, consumers have increasingly higher expectations for products and services that are more sustainable in terms of economics, natural resource depletion, and global warming potential (GWP), as well as the health and safety of producers and consumers. Consumers were willing to pay a premium for plants in containers labeled as "sustainable," but the premium differed with the type of sustainable containers (Yue et al., 2010). This research group found that there was a higher demand for locally grown landscape plants than for plants labeled as certified organic. Biodegradable and compostable pots were more desirable to surveyed customers than recycled pots.

The majority of the nursery and greenhouse crop producers surveyed in 2010 had incorporated sustainable practices in their systems, and one-fourth were considering options for becoming certified as sustainable (Dennis et al., 2010). There are a few sustainability certification programs that have been established by industry groups or companies to document their commitment to minimal environmental impact production practices. Veriflora [Emeryville, CA (Veriflora, 2012)] and Certified EcoSource by Ball Horticultural Co. (West Chicago, IL) are examples of such certificates. Several states have certification programs that encompass best management practices with varying degrees of crop specificity. Although laudable, such programs are usually not based on international standards for measurable environmental impact factors.

Unfortunately, there are few standards being used in the claims of some products and services, and the terms being used are often loosely defined. One tool for quantifying the environmental impact of a product or service that has been accepted in the scientific community is life cycle assessment (LCA). The initial driving force for the development of such tools was the environmental regulations by the U.S. Environmental Protection Agency and various European governmental agencies as they sought to measure the potential impact of various processes as a basis of policy and standards. For example, fair and comprehensive registration of pesticides for use on certain crops in defined environments requires rigorous and reproducible scientific assessments. Potential impact is expressed in terms of producer and consumer safety as well as operational impact categories such as global warming/climate change potential, toxicity, acidification, and resource depletion. International standards for assessing various environmental impacts became even more important as international trade exploded in recent decades. The International Organization for Standardization [ISO (Geneva, Switzerland)] published a revised standard in 2006 (ISO, 2006), and guidelines in PAS 2050 (British Standards Institute, 2011) provide additional details.

Materials and methods

LCA is a systematic process accounting for diverse environmental impacts of interrelated input components

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046

and processes of a product or practice during its complete life cycle, cradle-to-grave (Baumann and Tillman, 2004). A *carbon footprint* (the total amount of greenhouse gas emissions caused by an organization, event, product, or service) is the most common focus of LCA analyzing system components and their interactions. The carbon footprint of a product or activity is expressed in kilograms of carbon dioxide (CO_2) or equivalent emitted (CO_2e). Other questions that could be addressed by an LCA relate to a product's *water footprint* (the water used, both directly and indirectly, by an organization, event, product, or service), *toxicity potential* (releases that are toxic to humans and/or the environment, both acute and chronic), or some other environmental impact measure.

LCA includes information about an entire system for a product or service, usually cradle-to-grave, and the three primary life phases: production phase, use phase, and post-life phase. An example of boundaries and material and product flow for the life cycle of a 2-inch-caliper field-grown shade tree is illustrated in Fig. 1. The *production phase* encompasses the assimilation of inputs and the processes required to produce the product. The *use phase* includes the impact of the product during its useful life. The *post-life phase* assessment focuses on the impact of the product as it is reused, recycled, or disposed. Information about each primary life phase could help determine the primary factors in environmental impact. For example, it would be expected for the impacts of plastic nursery containers to occur primarily during the production phase (use of energy, petroleum, etc.) and in the post-life phase with little direct impact during the use phase (crop production). The primary contribution to the carbon footprint for fresh fruits and vegetables would be expected to occur during production, storage, and transport (Edwards-Jones et al., 2008). Any negative carbon footprint of field-grown shade trees occurs primarily during production and transport, while significant positive impact occurs during the use phase as growing trees sequester carbon, release oxygen, shade structures and microenvironments, absorb air pollutants, and so on (Ingram, 2012; McPherson et al., 2007).

The functional unit for a product or activity targeted by an LCA must be defined. A 2-inch-caliper field-grown tree, a 6-inch flowering potted plant, a standard size box of a specific vegetable, or a bushel of tree fruit could be functional units for an LCA related to horticultural crops. The units of all system inputs must be converted to that functional unit. For example, the amount of fertilizer, machinery time for a specific operation, and so on must be expressed relative to the functional unit.

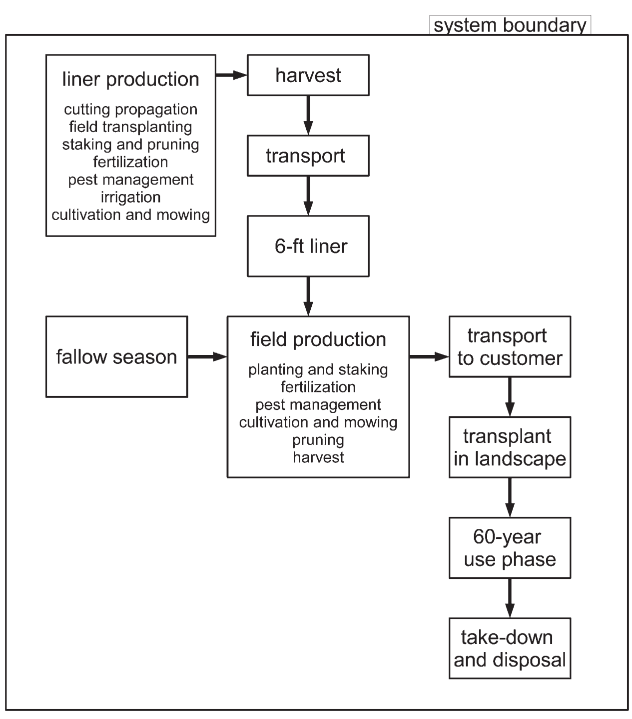

Fig. 1. System diagram and boundary for the life cycle of a 2-inch (5.1 cm)-caliper, field-grown shade tree (adapted from Ingram, 2012); 1 ft = 0.3048 m.

Inventory analysis is the base component of an LCA. All inputs and processes are inventoried, and the contribution of each to measurable environmental impact within the defined system boundaries is determined. Boundaries may include use, reuse, and maintenance. Boundaries may be referred to as cradle-to-grave or even cradle-to-gate, but defining what is the cradle and what is the grave or gate of a product or practice is an important issue. Cradle-to-grave refers to the impacts of a product during manufacturing, transport, and use as well as the impact of that product at the end of its useful life. The grave could be considered recycling or being put in a landfill. Cradle-to-cradle boundaries refer to the usefulness of products after their primary use-life (McDonough and Michael, 2002). The expectation of such a boundary definition is that products would have a "value" at the end of their primary useful life. Aluminum can recycling is one of the best examples. Recycling aluminum cans saves 95% of the energy used to make aluminum cans from virgin ore and diverts ≈1.7 billion pounds from landfills. Aluminum cans represent less than 20% of curbside recycling collections but 70% of the value thus paying for collection of other materials (Can Manufacturers Institute, 2011).

Ideally, an LCA would inventory the raw materials and processes used in the production of all system inputs, but that is not always possible. The differences in LCA boundaries may depend upon the availability of reliable impact data for the products used as inputs. For example, the boundary may be set for shade tree production at the life expectancy for a tree, at landscape installation, or at the end of production at the nursery. Another boundary could be the tree liner, or it could begin with a seed or cutting. The boundary may be set at the plug stage of floral crop production with certain known impact factors such as the carbon footprint or may include the analysis of inputs for plug production as well.

Energy consumption (mixing, transporting, etc.), resource use (oil, nutritional ions, etc.), wastes (packing materials, etc.), or byproducts in production procedures are included in the inventory. Some have reported the embedded energy in a product or process. Although embedded energy constitutes most, if not all, of the carbon footprint of some products or processes, it often does not account for the total footprint. Certain inventory components may be available through recycling from other interrelated procedures in the system. Therefore, interaction of elements in the product cycle must be defined. A byproduct of one operation in the system may be an input for another step in production. For example, burning of wastes from one operation may partially fuel a greenhouse furnace.

A difficult step in developing an LCA for horticultural products is determining the footprint of inputs inventoried because complete information is simply not available for a diverse yet specific set of inputs. Such information is available in published databases for some, but use of general information in a specific horticultural system can lead to errors in interpretation. Variation in the impact of similar products can be illustrated by the variation in the carbon footprint among forms of nitrogen fertilizer. For example, the carbon footprint of ammonium nitrate per kilogram of nitrogen (N) (14.35 kg CO_2e per kilogram N) is 85% greater than that of urea (7.85 kg CO_2e per kilogram N) (Ingram, 2012; Snyder et al., 2009).

International standards define the environmental impact measures in an LCA. The primary measure has been greenhouse gas emissions. Unfortunately for the greenhouse industry, the term "greenhouse gases" in the context of global environmental impact refers to emissions that add to the atmospheric carbon dioxide concentrations or GWP. The primary greenhouse gas is CO_2, and the GWP of any greenhouse gas is compared with the GWP of CO_2, which is set at 1.0. A carbon footprint is expressed as the GWP in net kilograms CO_2 [or equivalence of other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O)] released or sequestered per functional unit of the product or practice. The GWP of 1 kg N_2O is 296 kg CO_2e and 23 kg CO_2e for 1 kg CH_4, although their concentrations and emissions are small compared with CO_2. CO_2 evolution through such processes as burning fossil fuel has negative impact and CO_2 uptake or sequestration has a positive impact on the atmosphere. Although a relatively small volume of N_2O is emitted during manufacturing and after application of fertilizers, the environmental impact can be significant. It is interesting to note that N_2O emission represents 4.65 kg CO_2e of the GWP per kilogram N (Snyder et al., 2009). For urea, that means 4.65 of the 7.85 GWP per kilogram N would be from N_2O emissions.

Although the most common unit of an LCA is the carbon footprint, other environmental impact measures include the acidification potential, the eutrophication potential, or human and ecosystem potential toxicological impact. Acidification potential refers to the ability of certain substances to buildup and release hydrogen ions, thus acidifying that environment. For example, air pollutants such as sulfur dioxide and N_2O interact with water to form acids and result in acid rain. Eutrophication is the enrichment of nutrients in a certain place, be it water or soils, expressed in phosphate equivalents. It is important to note that eutrophication differs regionally and is influenced by geology and climate, among other things. For example, a retention basin or pond in a container nursery system could be enriched by runoff nutrients and could impact algae growth and oxygen content of the water, resulting in reduced irrigation water quality. The importance of inclusion of certain environmental impact measures in an LCA will be dictated by the purpose of the study, the nature of the system being analyzed, and its specific location.

After the impact measures and potentials of all individual input components and the interrelated procedures are defined and converted to the chosen functional unit, the calculations are relatively simple. The impacts are usually additive, and spreadsheet or database programs can be used to speed up the calculations and allow repeated queries of the model based on scenario changes.

The potential for errors or bias in an LCA is magnified during interpretation and validation. First, as true with any science-based study, the interpretation should be within the predetermined scope of the LCA. The degree of uncertainty or a sensitivity analysis for individual components can be used to reduce or identify potential errors or bias. The findings of an LCA must be judged through the presentation or availability of key input data, inherent assumptions about the system and its components, and the calculations used in the analysis. The procedures should follow the published international standards for an LCA (ISO, 2006), and underlying data and calculations should be published for others to review and scrutinize. The international standards do not contain guidelines for every situation, particularly agricultural operations. Therefore, review and acceptance by interested parties with diverse perspectives is a strong validation for the results and their interpretation. Publishing in a refereed journal would be one avenue to gain validation. The ultimate validation would be a third-party certification, an unbiased individual or group knowledgeable of the standards who can control the details of the entire LCA.

Results and discussion

Relevance of LCA to horticultural industries. The horticultural industries have a big stake in the discussion of sustainability and LCA will be a primary tool used to define it. Defensible, accurate, science-based information is a must for these industries as they enter the national conversation, internally as well as with external interest groups and consumers. Science-based information generated by LCA studies will also allow producers to determine which practices contribute most to the carbon footprint of their products and assess the potential impact of changing practices or input components on that footprint, other environmental impacts, and related production costs.

Life cycle assessment can be used to study the production system as a whole or to analyze individual system components. The potential impact of biodegradable and/or plantable containers and biodegradable plastics can be assessed using LCA. Potential impacts of reuse and recycling can be studied with LCA, as well as long-term ecoservices of living plants. Such advances or alternatives can be assessed based on not only environmental impact but can relate this information to economic impact and consumer preferences.

Data on the carbon and water footprint of inputs are readily available for some products and systems. This is not generally true for horticultural products and services. However, it is documented that the use of plastics in production is a significant contributor to the carbon footprint of landscape and floral plants and many vegetables (Kotrba, 2008). Biodegradable containers can be manufactured from biomass such as corn (*Zea mays*), straw, and coir or perhaps can be manufactured from plastics that are biodegradable. Although the carbon footprint of waste from biodegradable containers would be expected to be smaller than for standard plastic containers, the carbon footprint of biodegradable container production may or may not be smaller.

The potential impact of reusing inputs in crop production can also be studied through LCA. For example, production containers can be reused with the investment of energy to handle, transport, and clean the used containers. Plastic rowcovers and mulches can be used for multiple crops in a given season. In relation to an LCA, reuse means the functional life has been extended at some cost (environmental and economic), and two or more plant products are generated from that life extension.

Life cycle assessment can be used to study the potential carbon footprint impact of recycling. Recycling would result in the reuse of a material to make the same product or some unrelated product. Plastic containers, rowcovers, and mulches could be recycled for another use. Lower "value" plastic materials could be recycled to make plastic containers for the industry. An LCA could account for CO_2 released and/or lack of CO_2 released by extending the boundaries of the assessment on either end of the production timeline. In other words, the analysis could include the use of recycled materials in production or recycling materials after production to determine the true long-term impact of system modifications.

A major impact of landscape plants and plants in interior environments is through postproduction ecoservices. Trees obviously have a greater impact on carbon capture and sequestration, oxygen evolution, improved air quality, and microclimate modification than smaller plants. International LCA standards require the assessment of carbon sequestration over a 100-year period and provide procedures for documenting a weighted impact of carbon sequestration over a portion of that assessment period (British Standards Institute, 2011). Documentation of ecoservices of landscape plants in the urban and suburban environment can add science-based information to the public discussion of sustainability (Ingram, 2012; McPherson et al., 2007).

Life cycle assessment can also be used to determine the water footprint of a product or process. As in calculating a carbon footprint, the initial establishment of boundaries and scope for a water footprint is essential. The amount of water applied to a crop during production can be measured directly. The effectiveness of irrigation delivery techniques can be assessed in such a systems approach. As for carbon footprint, LCA boundaries for a water footprint could be set wide enough to include the amount of water required to produce inputs such as fertilizers, pesticides, and plastics.

Implications for information complied through LCA. The economic value of more sustainable products and practices will ultimately be determined by the consumer or through governmental regulations. LCA can result in decision aids to help horticultural crop producers determine the economic and environmental implications of production and marketing system modifications and perhaps provide reliable data for policy development. A properly designed LCA can help managers judge the environmental impact realities of practices. For example, is it better to grow bedding plant plugs in northern U.S. states or produce them in the tropics? What are the trade-offs between the transportation impact and the impact of greenhouse heating and the differential production time in different climates? Will the market support a higher cost for a particular product to reduce environmental impact or to support the local economy or local farmers?

LCA can be used in conjunction with system-component research on horticultural crops. Horticultural scientists conducting field research do so in the context of a system and have demonstrated transdisciplinary research for decades. LCA is one more tool in our arsenal to study system dynamics while engaging system-component research.

LCA has been employed to study the system components of container production (Kendall and McPherson, 2011) and field production (Ingram, 2012) of shade trees. The carbon footprints of no. 5 and no. 9 container-grown trees were reported to be 4.6 and 15.3 kg CO_2e, respectively, but the study did not include the impact of carbon sequestration during the production or the use phases. The primary contributors to the carbon footprint of a 2-inch-caliper red maple (*Acer rubrum*) tree (8.13 kg CO_2e) were equipment use during the production phase and in transporting and transplanting of the product (Ingram, 2012). More than 50% of the carbon investment in the field production phase occurs during harvest. Such information, along with economic data, can be used in considering alternative procedures that could reduce the carbon footprint during production. However, ecoservice through carbon sequestered during the "use phase" of this shade tree would be several hundred times the amount of carbon invested in its production phase. The weighted impact of sequestered carbon over a 60-year life of a red maple during a 100-year assessment period was 901 kg CO_2e minus an investment of 92.9 kg CO_2e for end-of-life disposal (Ingram, 2012). Results from these two targeted studies illustrate that LCA will become an important tool in studying horticulture production systems and for communicating value to the public.

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